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On the binarity of the classical Cepheid X Sgr from interferometric observations⋆ *(Research Note)*

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Preprint online version: November 21, 2012

ABSTRACT

Context. Optical-infrared interferometry can provide direct geometrical measurements of the radii of Cepheids and/or reveal unknown binary companions of these stars. Such information is of great importance for a proper calibration of Period-Luminosity relations and for determining binary fraction among Cepheids.
Aims. We observed the Cepheid X Sgr with VLTI/AMBER in order to confirm or disprove the presence of the hypothesized binary companion and to directly measure the mean stellar radius, possibly detecting its variation along the pulsation cycle.
Methods. From AMBER observations in MR mode we performed a binary model fitting on the closure phase and a limb-darkened model fitting on the visibility.
Results. Our analysis indicates the presence of a point-like companion at a separation of 10.7 mas and 5.6 mag$_K$ fainter than the primary, whose flux and position are sharply constrained by the data. The radius pulsation is not detected, whereas the average limb-darkened diameter results to be 1.48±0.08 mas, corresponding to 53±3 R$_\odot$. at a distance of 333.3 pc.

Key words. Stars: variables: Cepheids – Binaries: close – Techniques: interferometric – Instrumentation: interferometers – Infrared: stars

arXiv:1211.4698v1 [astro-ph.SR] 20 Nov 2012

1. Introduction

Classical Cepheids are fundamental astrophysical objects, being the most popular primary distance indicators in the nearby Universe. These pulsating stars obey well defined Period-Luminosity (PL) relations, so that it is possible to derive their distance moduli by measuring periods and apparent magnitudes.

Cepheids can be used to trace the evolutionary properties of Helium burning intermediate-mass stars, as they are crossing the instability strip along the so-called "blue loops" in the HR diagram. However, the comparison between pulsation and evolutionary masses disclosed the problem known as *"Cepheid mass discrepancy"* (Cox 1980), due to the pulsation masses resulting systematically smaller than the evolutionary ones (see e.g. Bono et al. (2001); Beaulieu et al. (2001); Caputo et al. (2005); Keller & Wood (2006)).

Recently two double eclipse binary Cepheids have been identified in the Large Magellanic Cloud (Pietrzyński et al. (2011), Pietrzyński et al. (2011)), providing the first measurements of the dynamical mass of classical Cepheids with 1-3% accuracy, whose values support the pulsation masses, or the Mass-Luminosity relations based on evolutionary models that account for mild convective core overshooting (Cassisi & Salaris (2011); Prada Moroni et al. (2012)).

For non-eclipsing binaries, direct orbital determination of the companion by means of optical interferometry would provide dynamical mass determinations able to disentangle the mass discrepancy problem.

The binary fraction of the Cepheids has an impact on the Cepheid distance scale in the optical bands, since the companions are typically main sequence (MS) stars. The binarity analysis has been applied to a limited sample (Szabados 2003), but current estimates indicate that the binary fraction among MS B-type stars is of the order of 60–70% (Brott et al. (2011); Chini et al. (2012)).

In order to improve the current observational scenario we have observed the Cepheid X Sgr with the VLTI. This particular target was selected because: *i)* its trigonometric parallax has been recently measured by Benedict et al. (2007); *ii)* accurate radial velocity curves are available (Mathias et al. (2006); Storm et al. (2011)), and *iii)* it was suggested by Szabados (1990), on the basis of temporal changes in the γ-velocity, that X Sgr might be a binary, although this finding has always been controversial (Mathias et al. (2006); Groenewegen (2008)).

2. Observations and data reduction

2.1. Data acquisition

We observed X Sgr (HD161592, R.A. 17:47:33.62, Dec. -27:49:50.83, J2000) using VLTI/AMBER (Petrov et al. 2007) with the Auxiliary Telescopes. We used medium spectral resolution in the K-band (MR, R$\sim$1500, 2.1μm) and the fringe tracker FINITO (Gai et al. 2004) with a frame exposure time of 1 s. Observations were carried out with a maximum projected base-

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⋆ Based on observations collected at the European Southern Observatory, Paranal, Chile

Table 1. Log of the interferometric observations, with details on the SCIence-CALibrators sequence used and the optimal frame selection adopted for V^2 and ϕ. Magnitude and diameters of the two calibrators employed are shown.

Date	Target sequence	Baselines	% of frames for V^2	% of frames for ϕ
2011-04-24	CAL_2-SCI-CAL_2-CAL_1-SCI-CAL_1	D0-I1-G1	10%	100%
2011-05-03	CAL_2-SCI-CAL_1-SCI-CAL_1-CAL_2-SCI-CAL_2	D0-A1-C1	30%	100%
2011-05-07	CAL_1-SCI-CAL_1-SCI-CAL_1	D0-A1-C1	10%	100%
2011-06-11	CAL_1-SCI-CAL_1	K0-A1-I1	50%	100%
2011-06-25	CAL_1-SCI-CAL_1-SCI	K0-A1-I1	20%	100%
2012-03-31	CAL_2-SCI-CAL_1-SCI-CAL_1	K0-A1-G1	20%	100%

ID	Name	mag_K^a	θ_{UD}^a [mas]
CAL_1	HIP88839	2.070	1.881 ± 0.133
CAL_2	HD157919	3.203	0.947 ± 0.066

[a] Data from JMMC Stellar Diameters Catalogue - JSDC (Lafrasse et al. 2010)

line length of 127.8 m, corresponding to 3.1 mas spatial resolution, with the atmospheric seeing varied in the 0.7" ÷ 1.0" range.

For the sake of clarity, we distinguish here a Run A (six nights from 2011-04-24 to 2011-06-25) and a Run B (2012-03-31 night only, see Table 1 and Fig. 1). For each run we used a CAL-SCI-CAL observation scheme (Table 1) to better sample the variable instrument response during the night.

2.2. Data reduction

We used the *amdlib v3*[1] (Tatulli et al. (2007), Chelli et al. (2009)) reduction package in conjunction with custom IDL scripts for optimizing the fringe selection, computing averages, and calibrating the visibilities.

Each AMBER file contains many individual frames, which must be quality-selected to reject tracking losses in both FINITO and telescope guiding. Such events are associated to large values in the optical path difference (OPD) and cause a poor signal to noise ratio (SNR) of the fringes. We adopted the *amdlib* "PISTON+SNR" selection criteria, limiting the OPD variation below 8μm and keeping only the frames with the highest fringe SNR. The adopted percentage of frames, in the range 10 ÷ 50% for visibility V^2 and 100% for closure phase ϕ, has been optimized for each night separately (see Table 1).

Hence, we computed, for each file, the average values of V^2 and ϕ, weighted by the error estimate provided by amdlib; the same was done for the calibrators.

Finally, a night transfer function (TF) was computed using the calibrators listed in Table 1.

3. Results and Discussion

3.1. Visibilities and closure phases

Fig. 1 shows the calibrated V^2 as a function of the spatial frequency B/λ, while Fig. 2 displays the calibrated ϕ versus wavelength λ.

We see that the source is resolved, because V^2 is less than unity, and that significant deviations from a pure Uniform Disk (UD) are evident. This could indicate a possible detection of the Cepheid pulsation, or might suggest a more complex morphology, like that of a binary. In any case, in the ϕ plot we only see small deviations from zero, which is an indication that the companion, if present, should be faint and close to our detection limit.

[1] Available at http://www.jmmc.fr/amberdrs

Both plots, in particular the V^2, show that the error bars are clearly larger than the dispersion of the data points, indicating a correlated noise caused by the low-frequency variations (on time-scales of minutes) of the TF during the night.

3.2. Model fitting

3.2.1. Binary companion

Szabados (1990) suggested, on the basis of changes in the γ-velocity, that X Sgr might be a binary system with a period of ~507 days. The complex nature of X Sgr was further supported by Sasselov & Lester (1990) who spectrally found that line asymmetries and line-doubling were well beyond the typical Cepheids behaviour; in particular, the two absorption components showed different Doppler shifts, but they did not display secular velocity changes compared with the γ-velocity. This complex dynamical structure was also supported by other high-resolution (R~120,000) optical spectra by Mathias et al. (2006). They hypothesized a binary, or even triple, nature of X Sgr. The data available in the literature were analyzed by Feast et al. (2008) and by Groenewegen (2008) who also found evidence of binarity, these latter suggesting a slightly longer orbital period (~570 days).

In order to check the companion hypothesis, we performed a binary model fit to the closure phase ϕ. We decided to use only this observable, for its low sensitivity on the unknown radius variation, for which we adopted a crude UD estimate of $r_{UD} = 0.74$ mas, provided by the V^2 values at the largest baselines, namely the data from nights 2011-04-24, 2011-05-03 and 2012-03-31.

We started with Run A alone assuming no temporal variation in the binary configuration within the two months, which is a plausible assumption, considering the mentioned orbital period estimates. Therefore we fit the Run A data all together in order to increase accuracy. Run B was not included here, since it was acquired 10 months later.

We adopted a grid search on a wide parameter space in $\Delta x, \Delta y$, f and r_2, where $\Delta x, \Delta y$ are the R.A. and Dec. offsets of the companion (these are searched within a radius of 100 mas around the primary, see Absil et al. (2011)), f is the flux ratio of the companion to the primary, and r_2 is the companion UD radius.

We obtain the best fit result for a flux ratio of $f = (6\pm1)\cdot10^{-3}$ (corresponding to a 5.6 ± 0.2 magnitude difference), while r_2 tends to zero, thus confirming the presence of a faint and un-

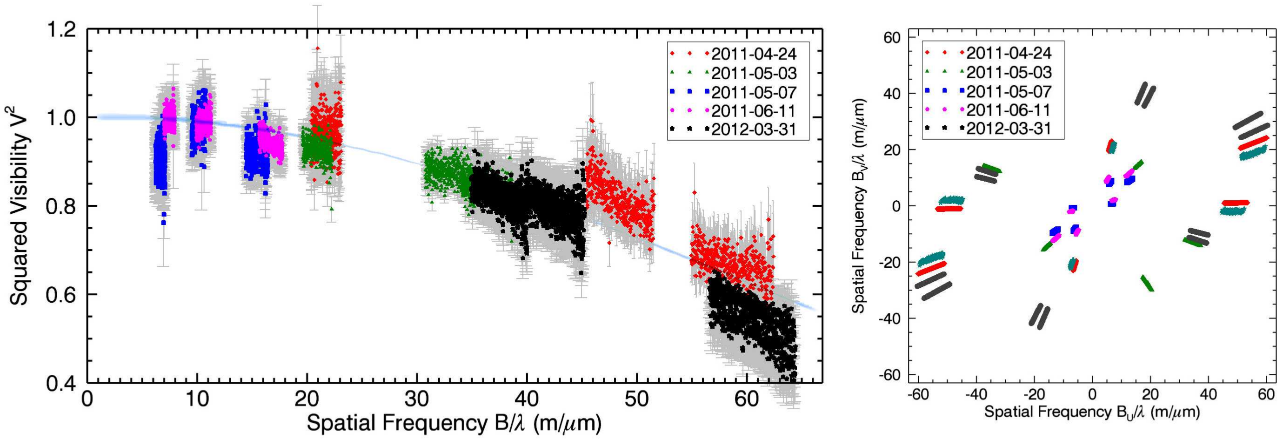

Fig. 1. Left: calibrated V^2 versus spatial frequency B/λ for the entire set of observations, superimposed to the average UD model (continuous line). Right: spatial frequencies (u,v-plane) coverage. Different colors and symbols refer to different observing nights (see legends). Note: the 2011-06-25 night is not plotted in the left panel, due to a very unstable TF for V^2.

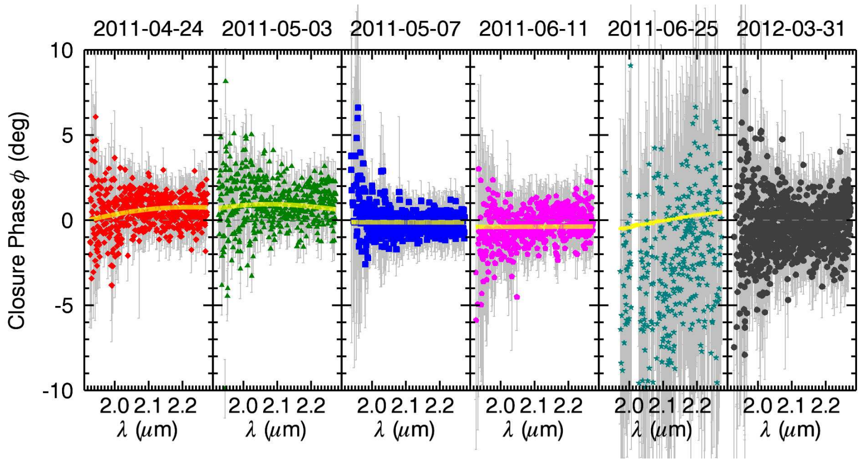

Fig. 2. Calibrated ϕ versus λ for the entire set of observations. Colors and symbols are the same as in Fig. 1. The yellow line shows the binary model described in Sec. 3.2 providing the best fit to the Run A observations. The dates reported above the panels refer to the observing nights.

resolved companion, whose position is constrained by a single and well defined χ^2 minimum at 7.15±0.04 S, 8.00±0.02 E mas from the primary (see Fig 3). The parameters of the companion are summarized in Table 2.

The fact that the best fit reduced χ^2 is significantly smaller than one is due to the large error bars associated to the TF, already described in Sec. 3.1.

To double check our finding, we built a series of synthetic binary models with different flux ratios and the same error bars of the real data, from which we derived a sensitivity limit of $f_{lim} = 2 \cdot 10^{-3}$, i.e. 3 times lower than the measured flux ratio.

To refine this result we removed our assumption of fixed binary configuration, in order to check if we could detect possible displacements among different nights.

Therefore, we repeated the ϕ fitting separately for each night of Run A, to find out if the location of the χ^2 minimum moves as a function of time (nights 2011-05-03/2011-05-07 and 2011-06-11/2011-06-25 were fitted as single points).

The corresponding χ^2 maps (Fig. 3, panel A) show several local minima within the 99% confidence interval, all of them having the same probability to be the true position of the companion. This shows us that a single baseline configuration is not sufficient to unambiguously locate such a faint object.

However, each χ^2 map shows a particular local minimum in the same position found using the entire data set, and even more importantly the little displacements of these minima are in the correct temporal sequence, as disclosed by Fig. 3, panel B.

This empirical evidence further confirms our detection of the postulated companion of X Sgr, and although current data do not allow us to constrain the orbit, we have a hint on the direction of its motion.

The binary fit for the single night of Run B also show the same kind of multiple minima χ^2 map (not displayed), but with no minima close to the quoted position, as expected after a time interval of ten months.

3.3. Angular diameter

To determine the mean Cepheid diameter, and possibly its variation, we fit the V^2 separately for each night by fixing the binary parameters (Table 2) and varying only the primary radius r_1. Following Kervella et al. (2004), we adopted the Limb Darkening (LD) intensity profile by Claret (2000).

The radius r_1 only depends on the mean value of each visibility spectrum ($< V^2(\lambda) >$), whose error bar we computed as the

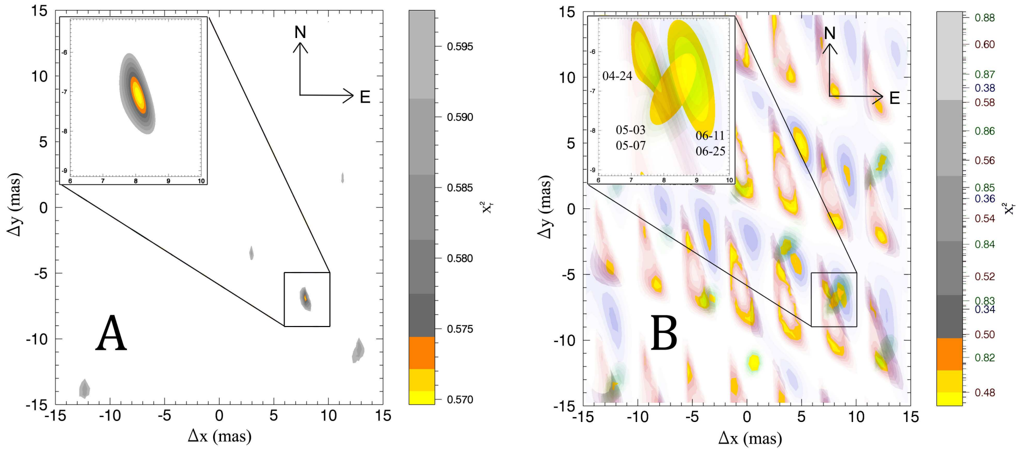

Fig. 3. Portion of the reduced χ^2 map on the R.A. and Dec. offsets obtained by A) fitting the ϕ of the Run A data sets together with a point-like companion model at fixed flux ratio $f = 6 \cdot 10^{-3}$, and B) for individual observing nights: red for 2011-04-24, green for 2011-05-03/07, and blue for 2011-06-11/25. The $1 \div 3\sigma$ confidence contours colours range from yellow to orange.

Table 2. Parameters of X Sgr companion, and LD diameters. Random errors (first ones) and systematics (second ones) are distinguished.

Δx [mas]	Δy [mas]	r_2 [mas]	f
8.00±0.02 E	7.15±0.04 S	<0.5	$(6\pm1)\cdot 10^{-3}$

Phase[a]	Date	θ_{LD} [mas]
0.83	2011-05-03	1.47±0.01±0.04
0.54	2011-04-24	1.36±0.09±0.04
0.35	2012-03-31[b]	1.59±0.08±0.04

[a] The pulsation phase was estimated using the formula provided by Szabados (1989) for constraining the pulsation period and the epoch of maximum of the different data sets.
[b] For the 2012-03-31 night a pure LD model is adopted, given the undetermined binary parameters.

quadratic sum of the weighted average error plus the correlated component due to the TF variation[2].

For the diameter determination we only took into account the nights 2011-04-24, 2011-05-03 and 2012-03-31, which have sufficiently long baselines and good quality. The night of 2011-05-03 plays a key role in this context, since it shows a pure random error with a negligible correlated component.

Table 2 provides, in the bottom section, the best fit LD diameters as a function of the Cepheid pulsation phase, computed following Szabados (1989).

In the table we distinguish the random errors and the systematics coming from the uncertainties in the calibrator diameters (Table 1). Note that the latter are larger than the former only for our best data set, namely the night 2011-05-03, showing the importance of using many different calibrators when a very accurate diameter measurement is required.

The differences in the three diameter estimates, within $\sim 1\,\sigma$ from each other, do not allow us to positively detect the radius pulsation, and are probably due to the mentioned TF temporal variation. The same limitation was also found by Kervella et al. (2004) using interferometric data collected with VINCI at VLTI.

[2] where the latter was estimated, for each visibility spectrum, as the squared difference between the r.m.s. of the error bars and the r.m.s. of the residuals with respect to a smooth polynomial fitting.

Table 3. Recent X Sgr radius estimates.

Article	Radius [$R_\odot$]
This paper	53 ± 3
This paper[a]	55 ± 4
Kervella et al. (2004)	53 ± 3
Storm et al. (2011)[b]	50 ± 3
Groenewegen[b,c]	49 ± 3

[a] Solution obtained by neglecting the presence of the companion.
[c] IRSB method.
[c] Private communication.

Thus we only computed a mean physical radius of 53±3 $R_\odot$ by adopting the trigonometric parallax of 3.0±0.18 mas from the HST (Benedict et al. 2007). In Table 3 we compared it with recent estimates from both optical interferometry (Kervella et al. 2004) and Infra Red Surface Brightness (IRSB, Groenewegen (personal communication) and Storm et al. (2011)), having used the same distance for all of these measurements. Finally, we also report the radius obtained by neglecting the binary companion, which has a ~3% impact on the mean radius.

4. Conclusions

We found evidence of the binary nature of the Cepheid X Sgr by analysing new interferometric data collected with AMBER at VLTI. The main conclusions of our work can be summarized as follows:

i) Our analysis of the closure phase indicates that both the flux and the position of the companion can be constrained by our data sets. We find that the angular separation is 10.7 mas and that the companion is 5.6 mag fainter than the primary in the K-band.

ii) The data allow us to directly measure an average Limb-Darkening diameter of 1.48±0.08 mas (i.e. a physical radius of 53±3 $R_\odot$) which agrees, at 1σ level, with similar interferometric and IRSB mean radii for X Sgr available in the literature.

iii) We find that MR AMBER closure phases obtained from 3 baseline configurations have the sensitivity needed to detect companions around nearby classical Cepheids. This evidence

becomes even more compelling if we take into account that current data were collected in medium quality seeing conditions.

iv) The average visibilities of the 2001-05-03 night show that a non systematic error as small as 1% can be obtained with AMBER in MR mode in stable TF conditions. This would be sufficient to clearly trace the differential diameter pulsation in future measurements, provided that the same calibrator star is used for all the observations.

v) We find that, in the case of a binary Cepheid, the effect introduced by the companion on the primary radius measurement (∼3%) is comparable with the expected radius variation (∼5 ÷ 10%).

Acknowledgements. We are grateful to the Nice Observatory (France), and in particular to F. Millour, N. Nardetto and P. Cruzalebes for helpful discussions, and to M.A.T. Gronewegen and J. Storm for many useful insights concerning Cepheids and for providing us with their recent radius measurements of X Sgr.

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